Lunar Polar Volatiles: Assessment of the Current State of Knowledge

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Introduction

- **Background**
  - Lunar volatiles are potentially a valuable resource for exploration.
  - Understanding of volatiles is evolving as new data emerge and scientists synthesize data, theory, lab experiments, and models.
  - Data sets are nuanced in ways that are not always obvious to the outside observer.
- **Purpose**
  - To provide an overview of the present state of knowledge
  - To explain the level of certainty/uniqueness of the results
  - To interpret the findings for application to ISRU

Volatiles on the Moon

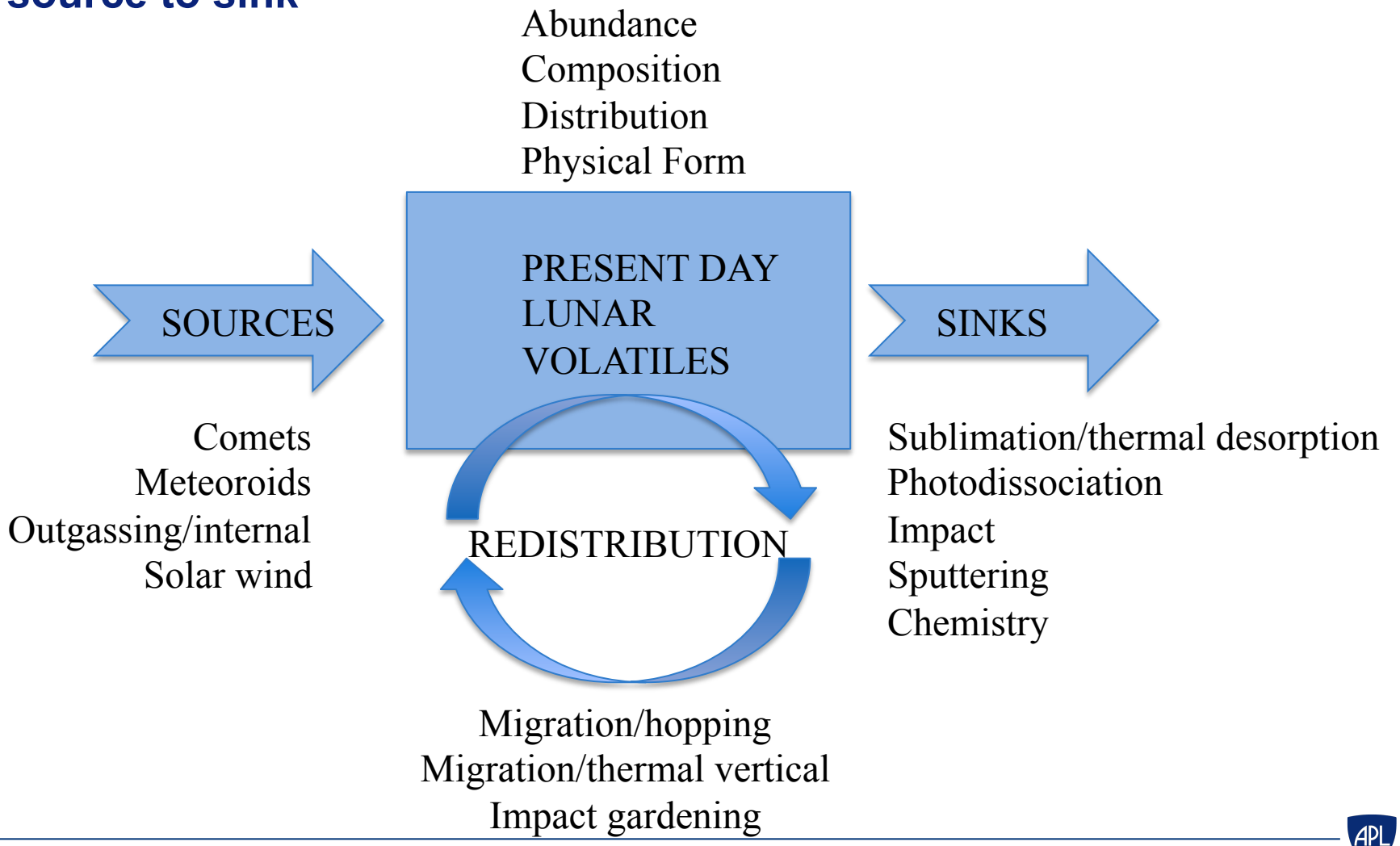
- **Three brands of volatiles:**
  - **Sequestered volatiles in cold traps**
    - **Episodic delivery of large quantities or constant delivery of small quantities or both**
  - **Internal volatiles trapped in minerals and glasses**
    - **Leftover from lunar formation**
  - **Global surface volatiles**
    - **Transient veneer either produced and lost in place diurnally or involved in migration**

Measurements of Polar Volatiles (Water Ice)

- **Current focus: Obtaining measurements of the following quantities**
  - **Abundance**
    - **Exploration rationale: assess value and extraction technique**
    - **Science rationale: tied to abundance of sources**
  - **Composition**
    - **Exploration: additional resources**
    - **Science: chemical fingerprint of source**
  - **Distribution**
    - **Exploration: scale of operations and extraction technique**
    - **Science: age of deposits; redistribution and retention processes**
  - **Physical State**
    - **Exploration: extraction technique; operational paradigm**
    - **Science: interactions between volatiles and regolith**

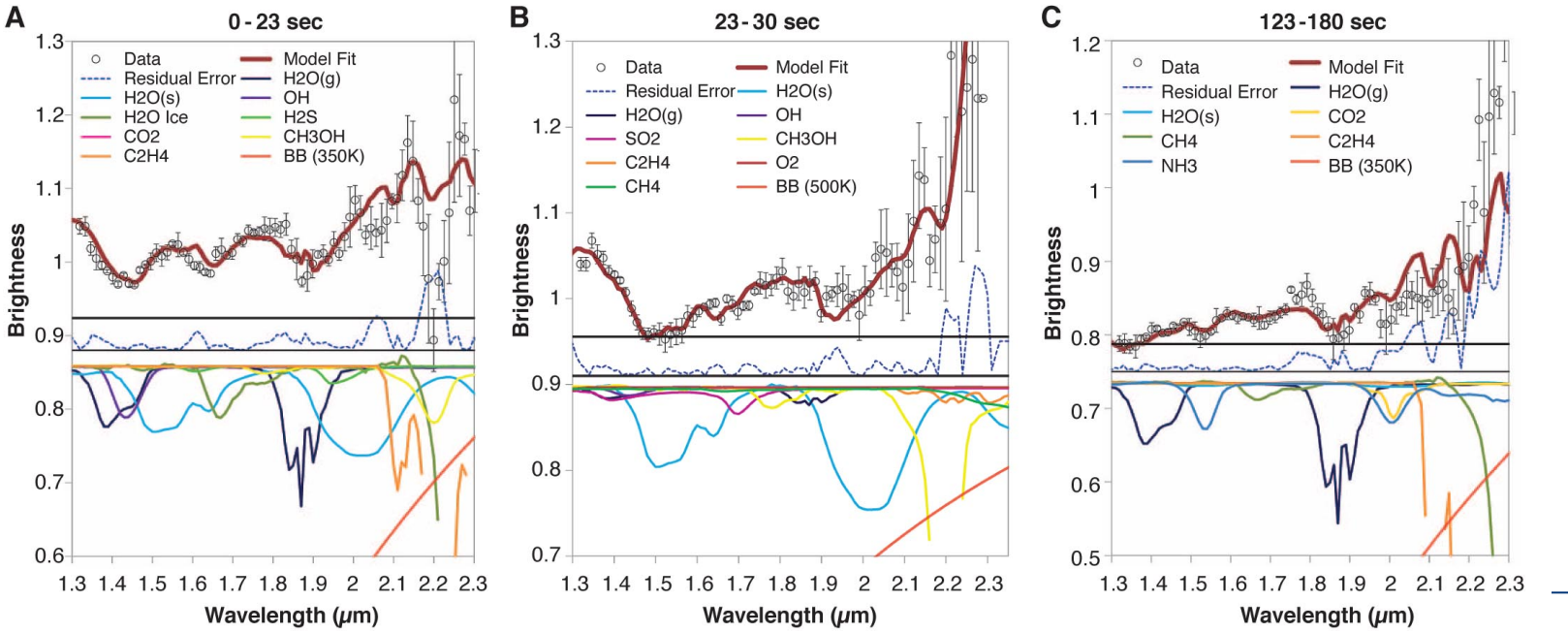
Processes for Polar Volatiles (Water Ice)

- **Current focus: Understanding the lunar water system from source to sink**



Existing Data: COMPOSITION

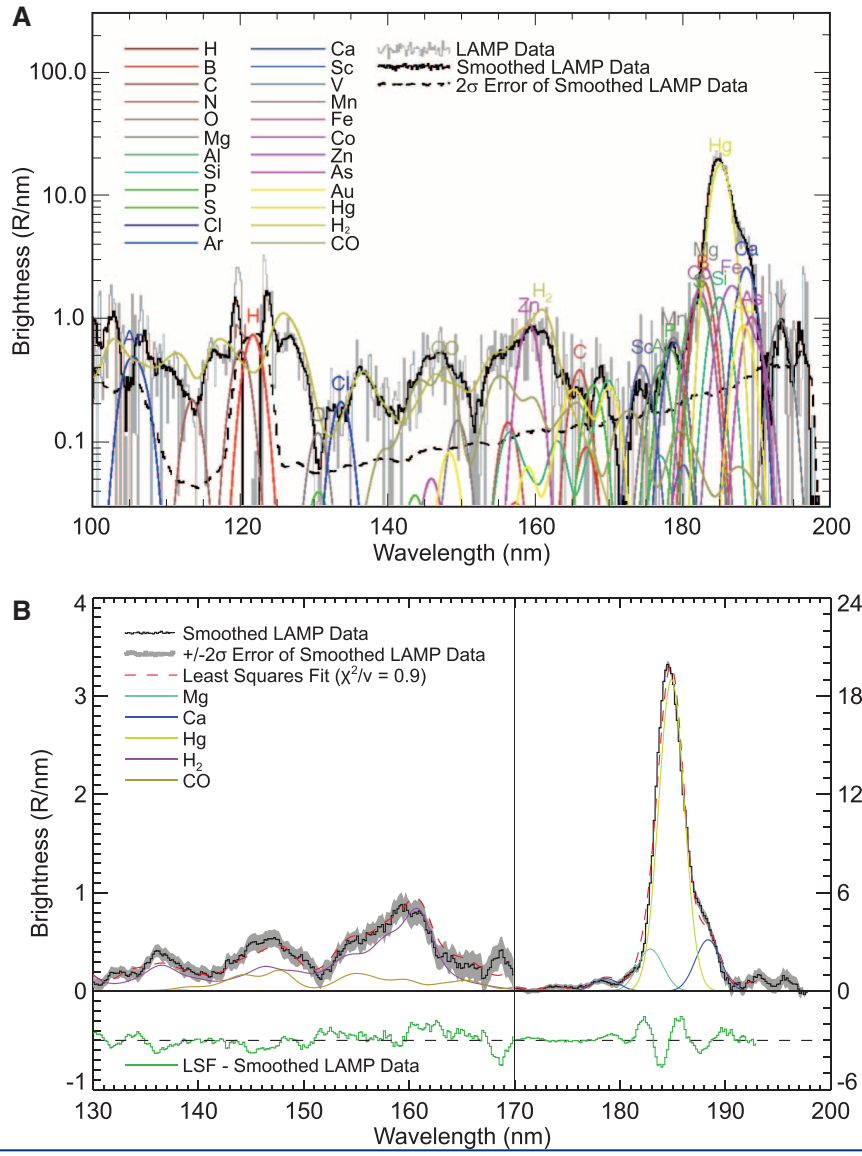
- **LCROSS impact into Cabeus**
- **Spectral identification of water in both solid and gas phases**
  - **High resolution spectra provide strong evidence for the chemical composition**
  - **LCROSS measurement has advantage of having lofted material into sunlight providing a strong illumination source**
  - **Question arises about any impact-induced chemistry and contributions from the impactor vs. the target material.**



Colaprete et al. (2010) Science

Existing Data: COMPOSITION

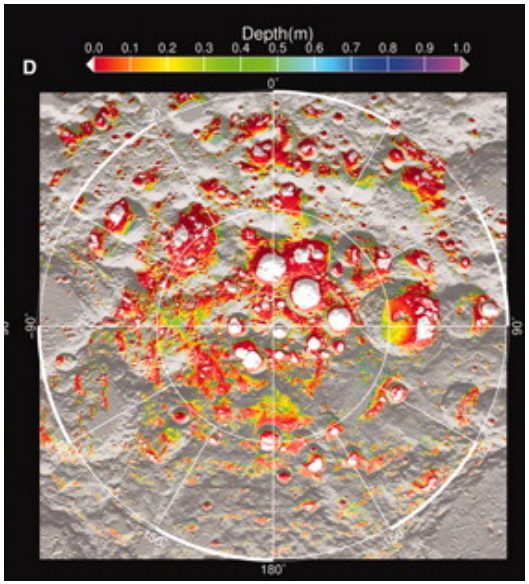
- LCROSS impact into Cabeus
- Spectral identification of other volatiles in the vapor
- From LCROSS
  - H_2S, SO_2
  - NH_3, CO_2
  - Hydrocarbons
  - OH
- From LRO
  - Hg, Mg, and/or Ca
  - CO
  - H_2
- From ground
  - Na



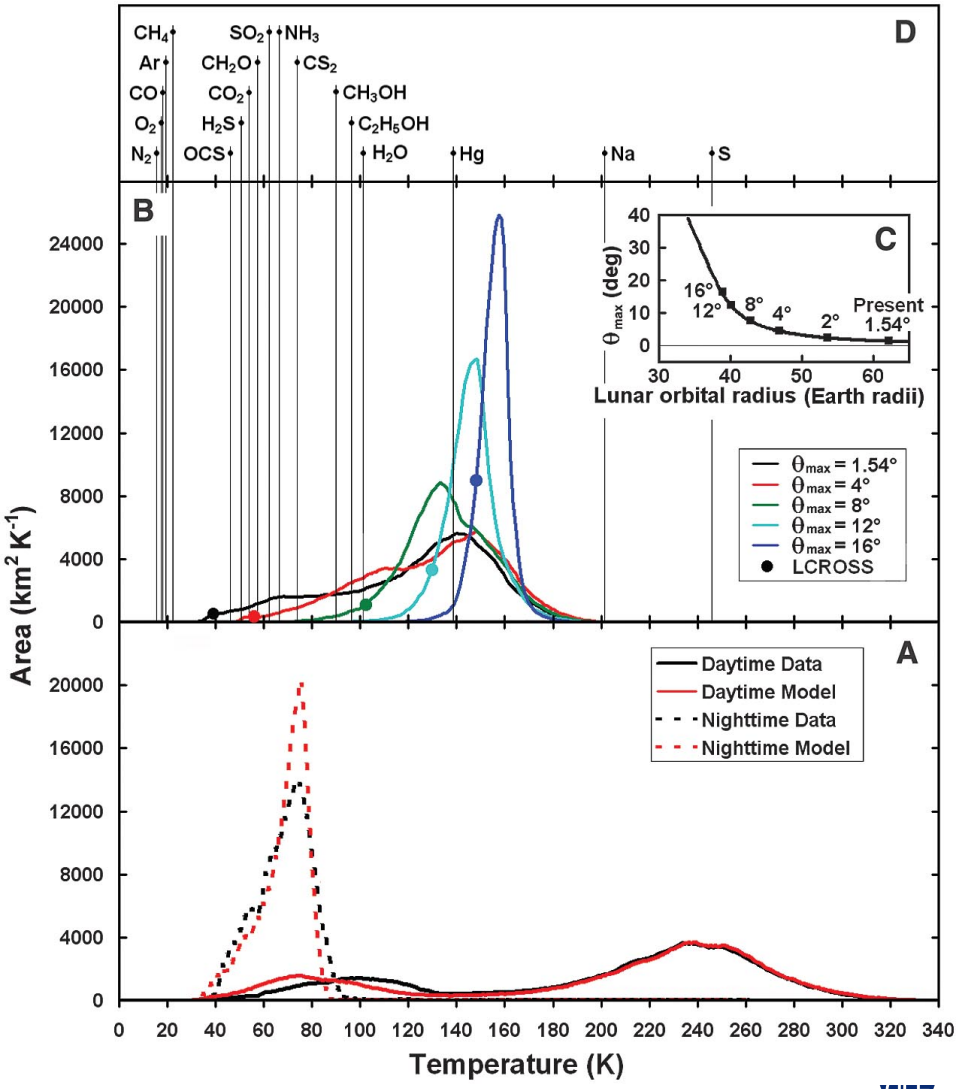
Gladstone et al. (2010) Science

Existing Data: COMPOSITION & DISTRIBUTION

- **LRO Diviner temperature measurements and thermal analysis**
  - **Provides map of where certain compounds are stable against sublimation**
  - **Modeling suggests the depth to a thermally stable layer**

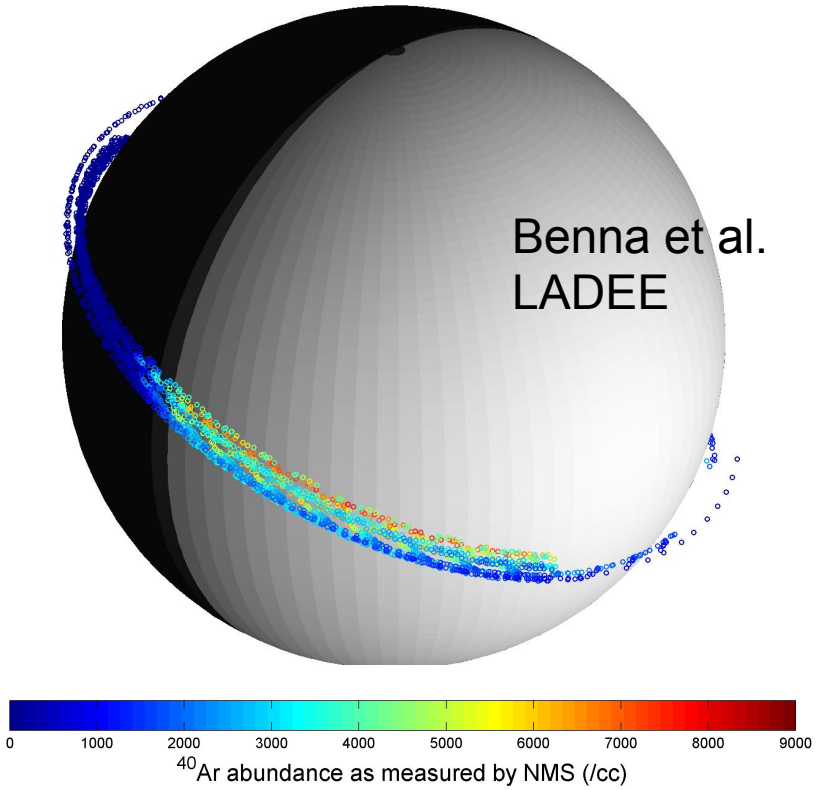


Paige et al. (2010) Science

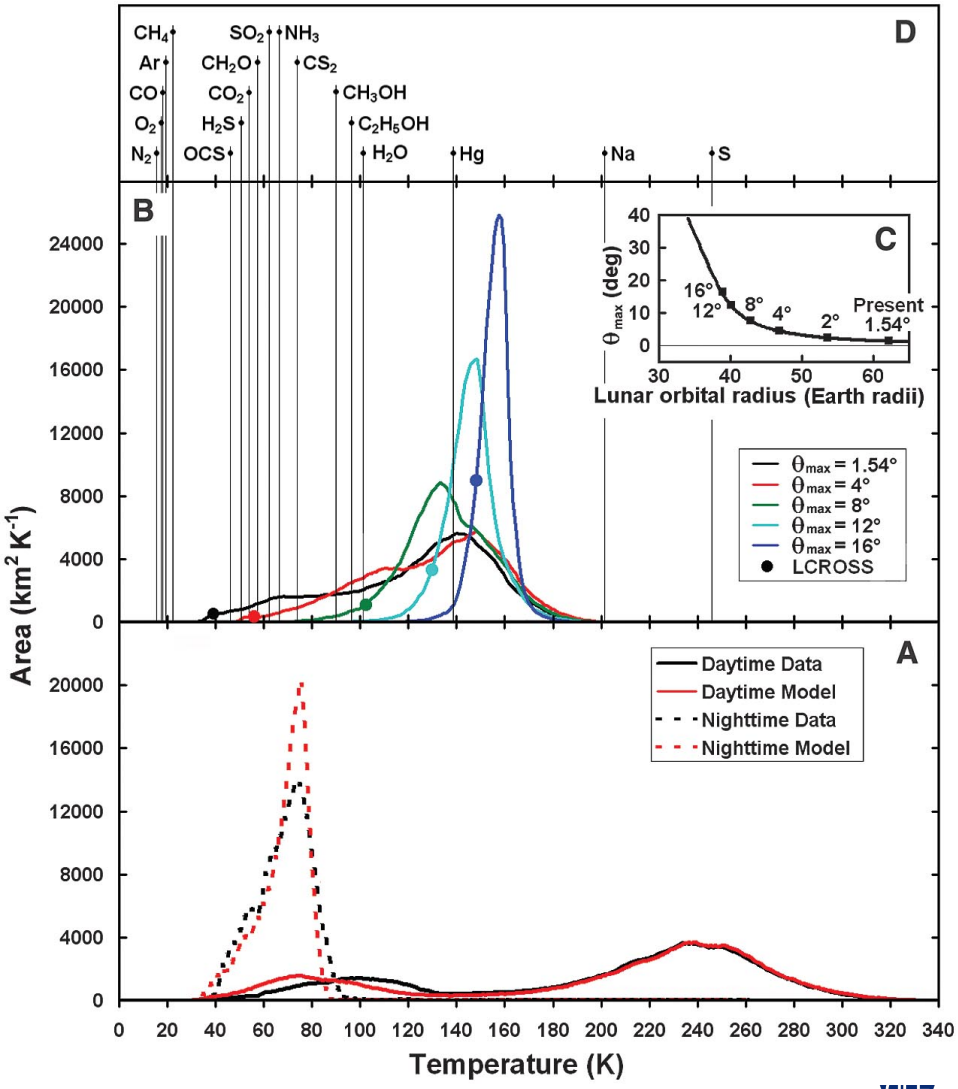


Existing Data: COMPOSITION & DISTRIBUTION

- **However we know that some exospheric species adhere to the surface at higher temperatures**
- **Timescale and surface interactions are important**



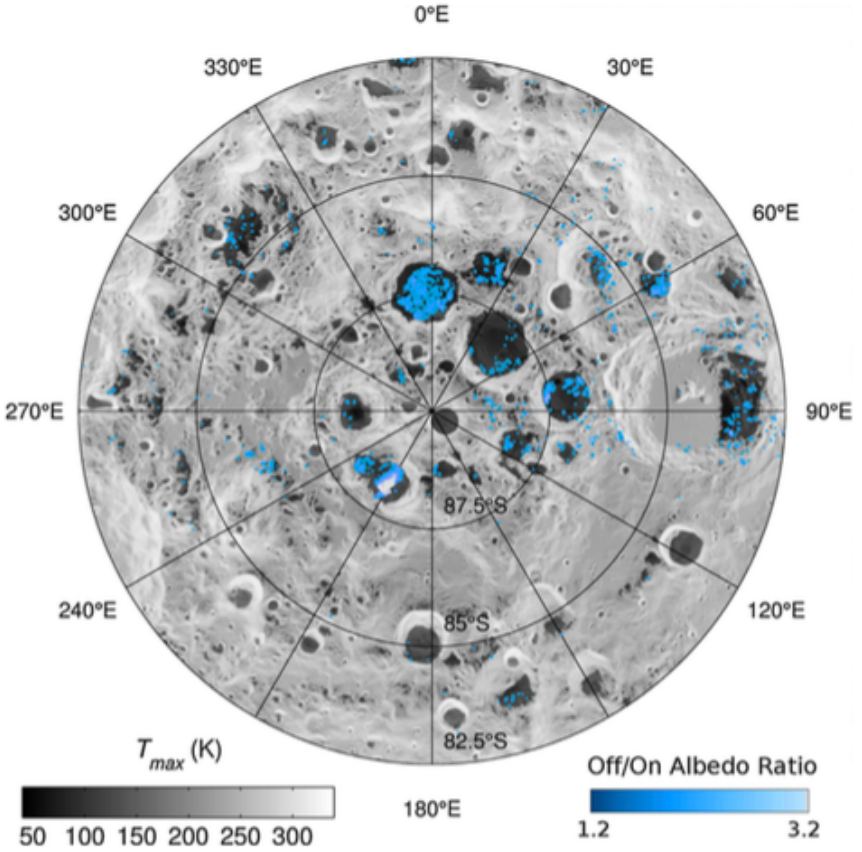
Paige et al. (2010) Science



Existing Data: DISTRIBUTION

- **Heterogeneous lateral distribution**
  - **Within a single PSR**
  - **From one PSR to another**
- **Surface frost**
  - **Using the signature of water ice at 165 nm, this analysis shows that surface frost is not evenly distributed in cold regions**
  - **LRO LAMP data are low illumination with very coarse spectral binning, thus are better as supporting data than standing alone**

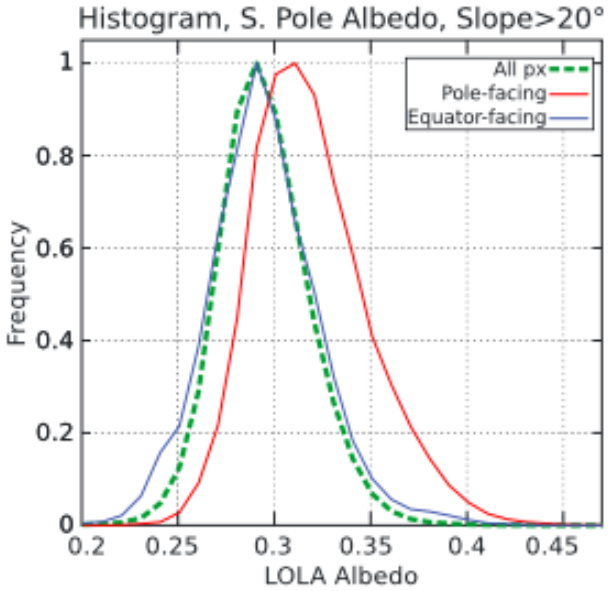
Hayne et al. (2015) Icarus

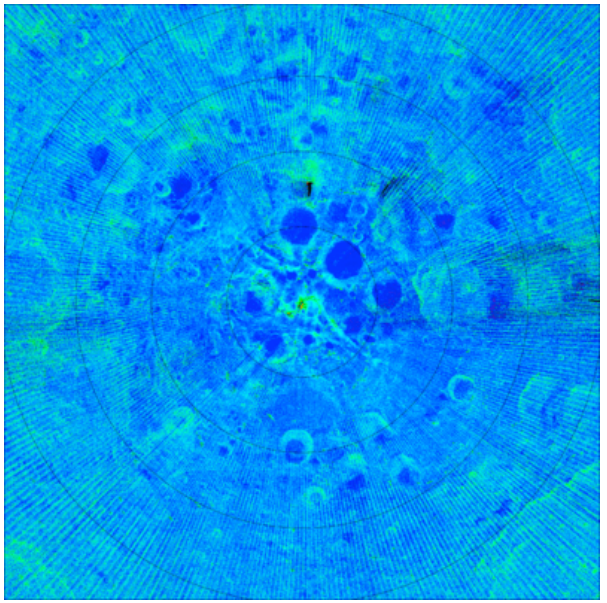


Existing Data: DISTRIBUTION

- **Apparent difference in equator facing slopes and poleward facing slopes**
- **LRO LAMP Lyman Alpha albedo and LOLA 1064 nm albedo show difference in poleward facing slopes**
- **Multiple effects can produce these including the presence of frost, but no certain conclusions can be drawn on these data alone.**

Lucey et al. (2014) JGR

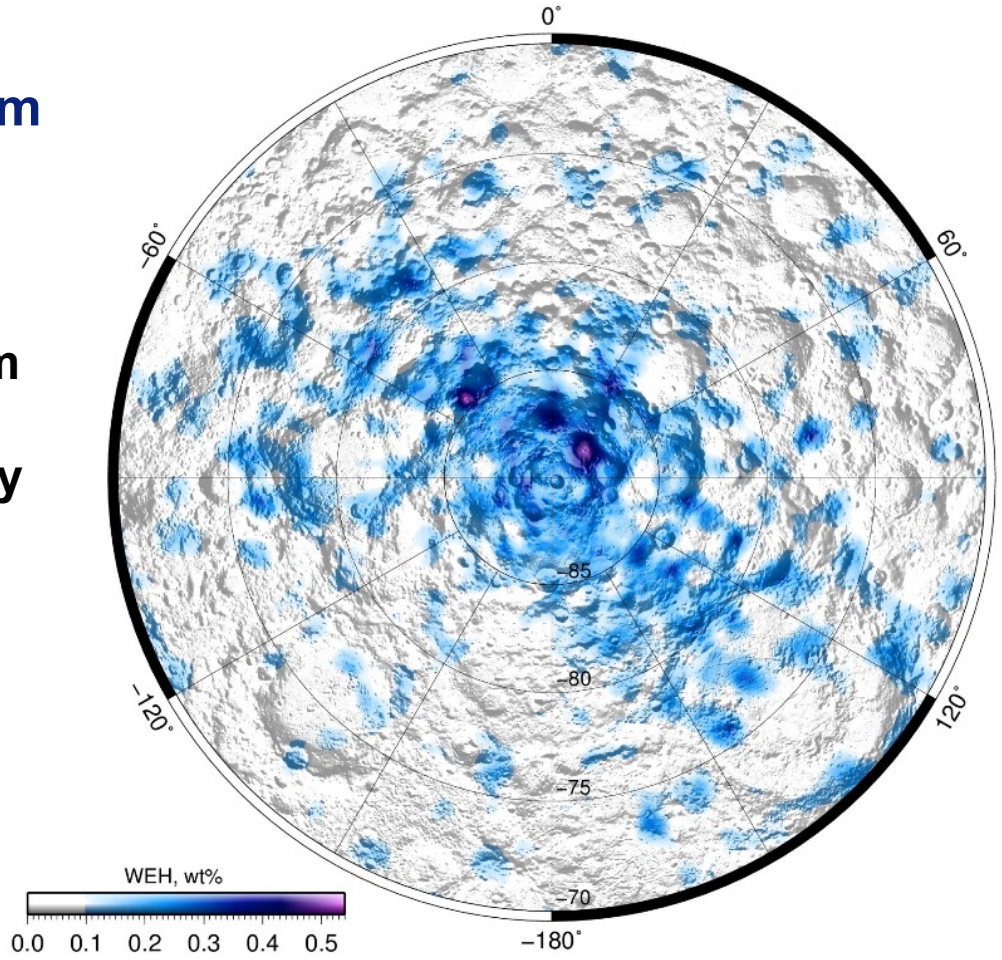




Gladstone et al. (2012) JGR

Existing Data: DISTRIBUTION

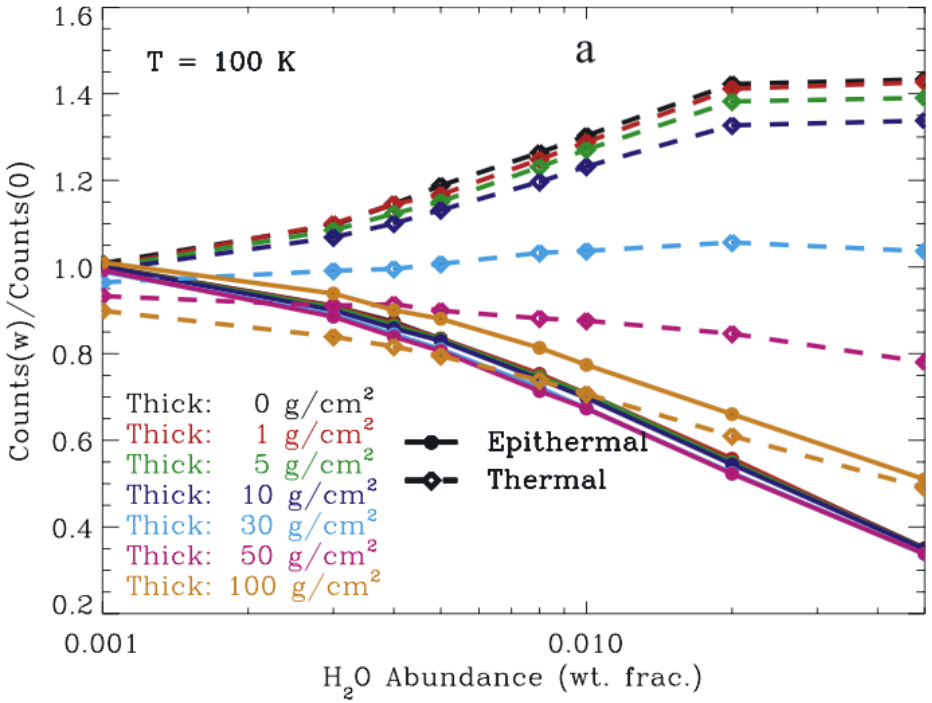
- **Neutron spectroscopy senses through the top 1 m of regolith.**
  - **Hydrogen values from depth-integrated measurements differ from surface frost measurements, especially in Shoemaker, Haworth, and Cabeus.**



Sanin et al., 2016

Existing Data: DISTRIBUTION

- **Neutron spectroscopy senses through the top 1 m of regolith.**
  - **Comparing neutron data from different energy ranges gives idea of depth distribution.**
  - **Many sites are most consistent with a dry layer about 10 cm thick over top of a layer with higher hydrogen abundances.**

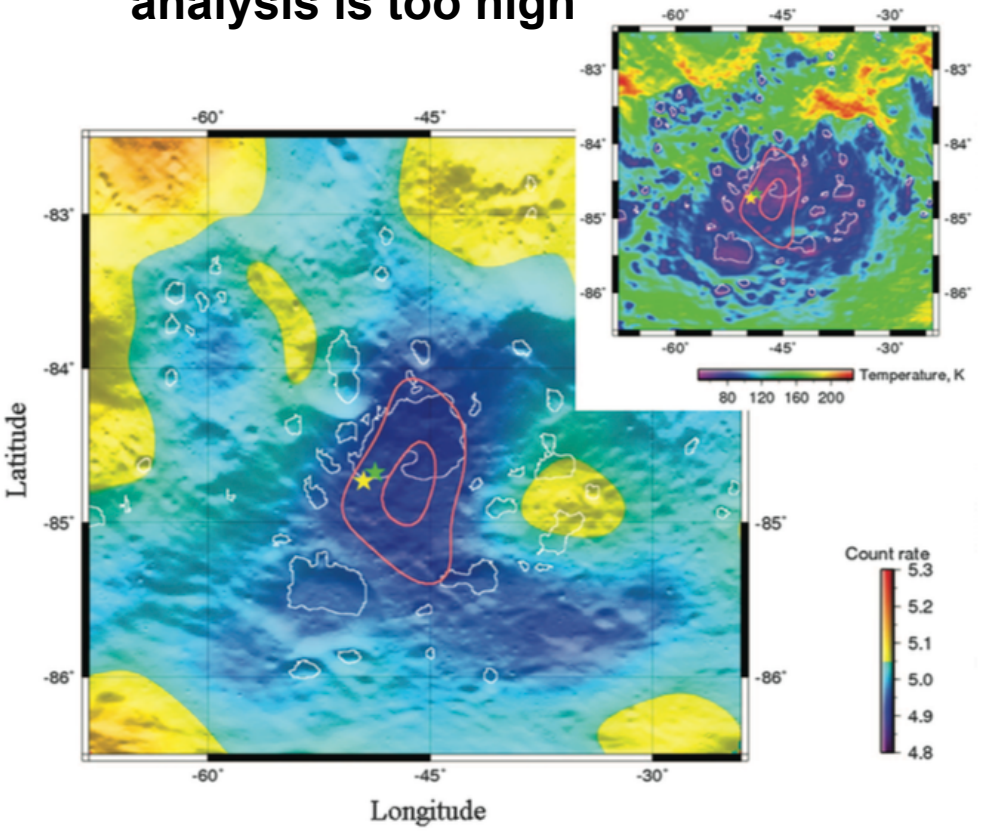


Lawrence et al. (2006) JGR

Existing Data: DISTRIBUTION/ABUNDANCE

- **Sub-pixel heterogeneity**
- **The LCROSS plume was consistent with 5% ± 3% water**
  - **Impact excavated to a depth of ~3 m and diameter ~20 m**
- **LEND neutron data are consistent with 0.45% water in Cabeus**
  - **Neutrons are sensitive to hydrogen content in top m**
  - **Neutron spatial resolution is > 20 m**

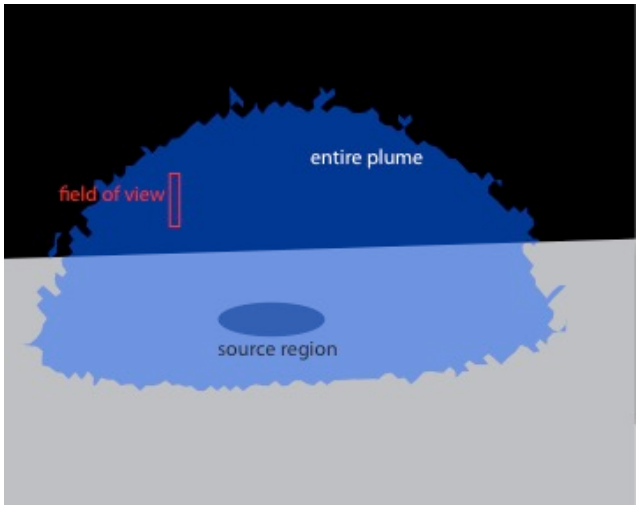
- **Possible explanations**
  - **Impact site was enriched laterally compared to surroundings**
  - **Water is enriched below 1 m depth**
  - **Inferred abundance from LCROSS analysis is too high**



Mitrofanov et al (2010) Science

From Observations to Abundances

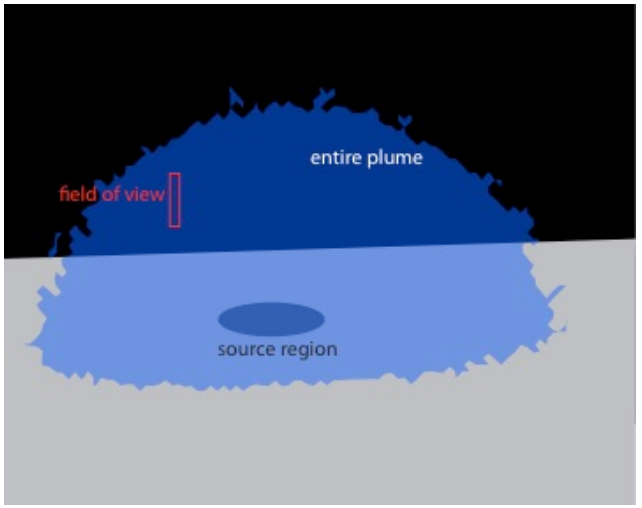
Observation of released vapor from LCROSS



Determine volatile abundances in the regolith

From Observations to Abundances

Observation of released vapor from LCROSS



Scalings:

Scale small field of view to global release

Relate to volume of regolith affected

Estimate efficiency of release

Determine volatile abundances in the regoli

LCROSS estimate of 5% water may not account for all of these

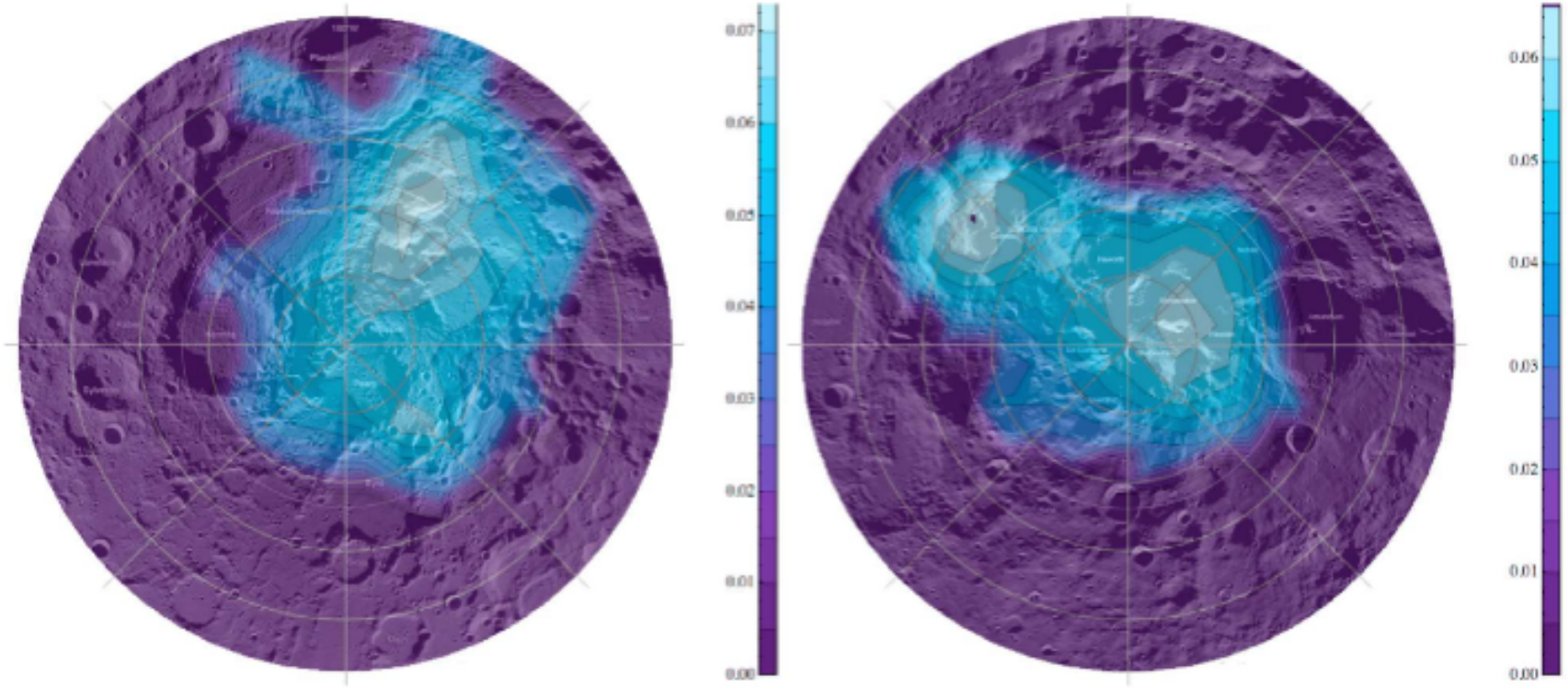
Species	Predicted amount (wt.%)	Mass (kg) released	Mass of regolith (kg)
Ca	11[C]	16	140
Mg	3.4[C]	3.8	110
Hg	0.28[D]	12.4	4400
H_2	0.047[A]	117	2.5e5
CO	0.023[B]	41	1.8e5

Hurley et al. (2012) JGR

[A]Mitrofanov et al. (2010), total H abundance
[B]Gibson and Moore (1973), relative proportion to H_2
[C]McKay et al. (1991), Apollo 16 soils average
[D]Reed (1999), extrapolation from Apollo drill core

Existing Data: ABUNDANCE

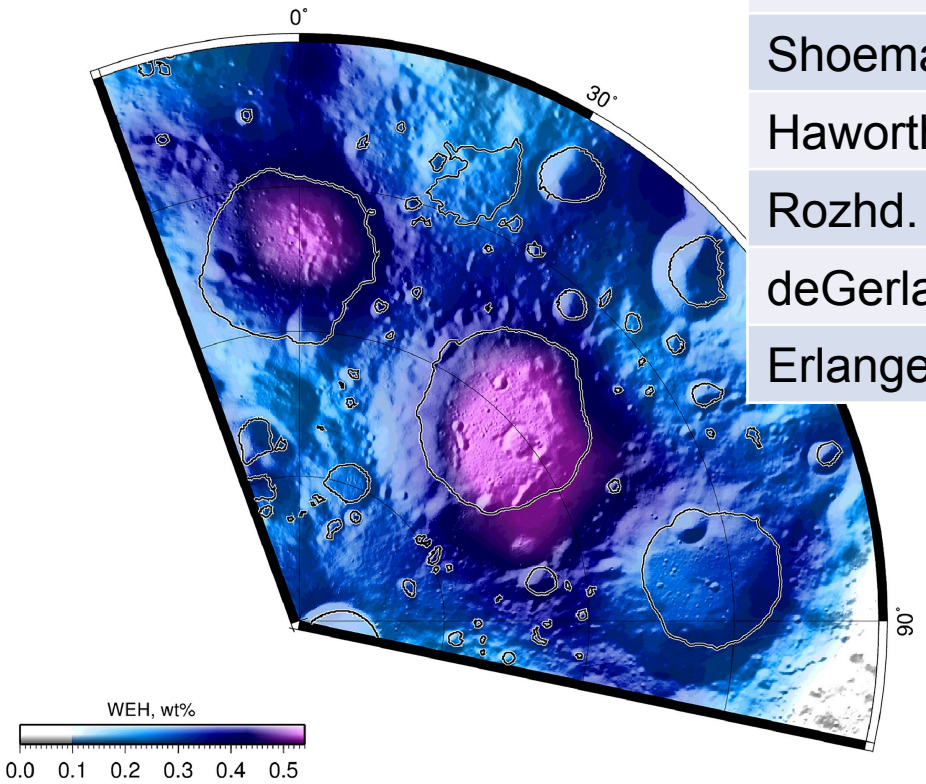
- **Neutron data**
  - **Average 0.01% wt. water equivalent hydrogen poleward of 80° and in the top 1 m**
  - **If water, amounts to 9.8 x 10^{10} kg (1/1000 of Lake Tahoe or .3 mErie)**



Miller et al (2012) JGR

Existing Data: ABUNDANCE

Crater Name	Mass of water in top 1 m (kg)	µEries (10^{-6} Lake Erie)	Lincoln Memorial Reflecting Pools
Cabeus	7.7×10^{10}	160	3900
Amundsen	5.1×10^{10}	110	2600
Shoemaker	1.9×10^{10}	40	970
Haworth	1.6×10^{10}	34	820
Rozhd. U	1.0×10^{10}	21	510
deGerlache	5×10^{9}	11	270
Erlanger	7×10^{8}	1.5	37



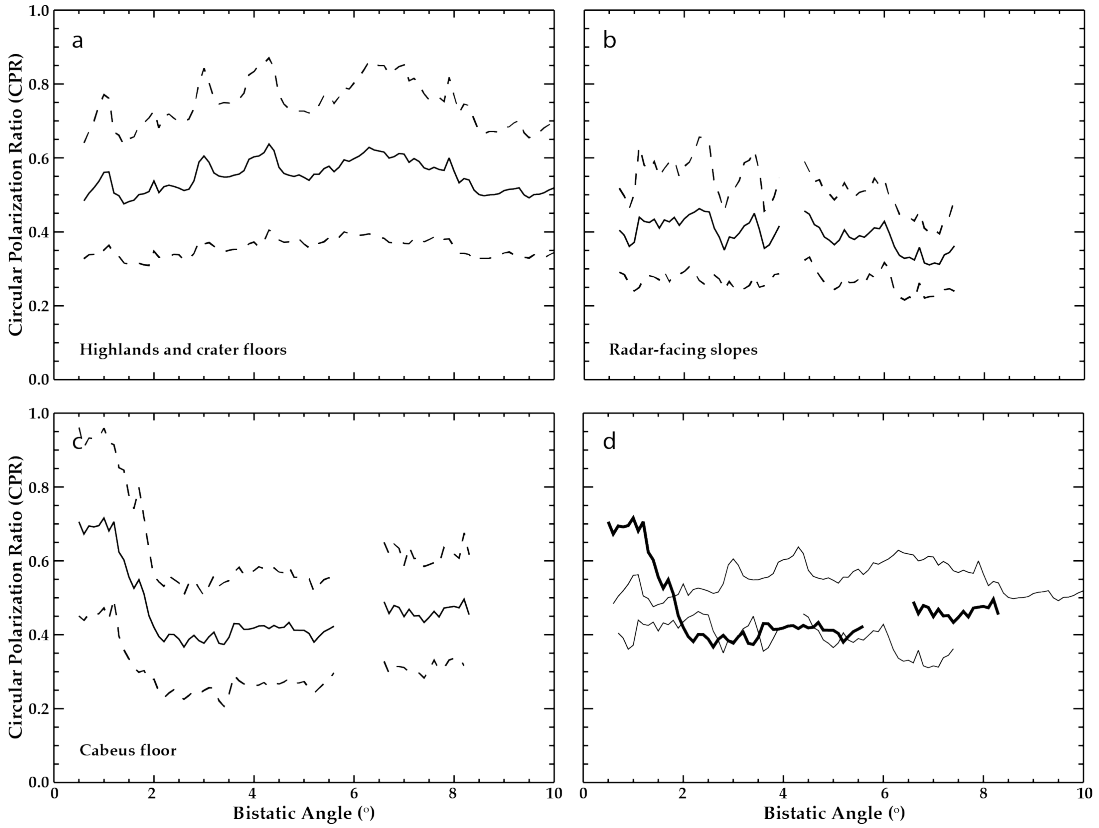
Sanin et al (2016) Icarus

Existing Data: PHYSICAL FORM

- Radar data
- Coherent backscatter is sensitive to relatively pure blocks of ice of scale > 10 cm.
  - On Mercury, radar data are consistent with thick, continuous, pervasive ice sheets in cold regions.
  - On the Moon, some craters show an anomalous signal where high circular polarization ratio (CPR) is observed inside the crater but not in the ejecta, unlike the majority of fresh craters
    - Spudis et al. interpret these as craters that have ice at the bottom.
    - This a controversial interpretation.
- We can rule out pervasive “skating rinks” on the Moon.

Existing Data: PHYSICAL FORM

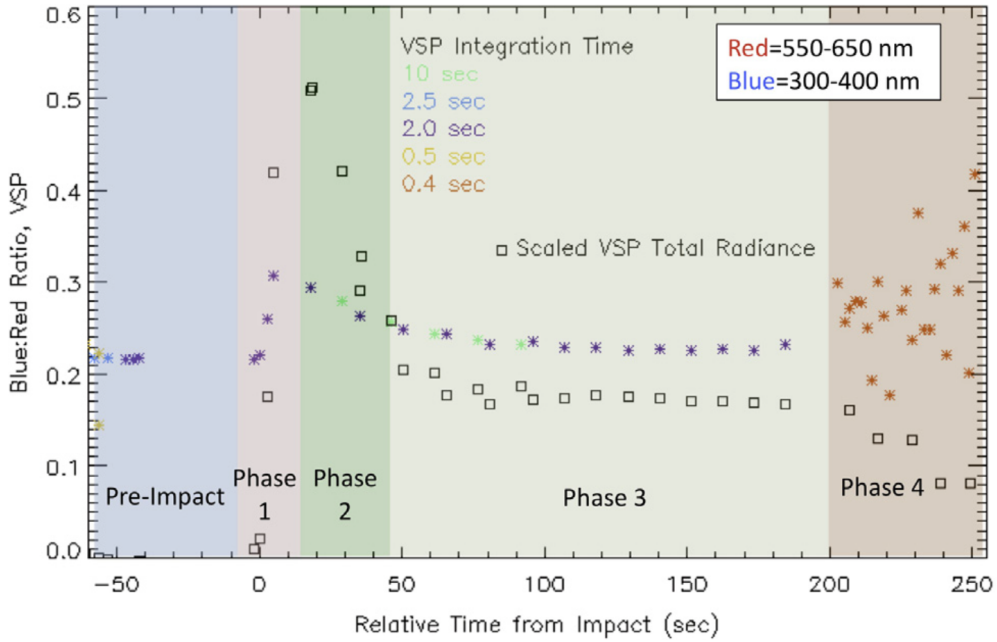
- **Bistatic radar uses the change in circular polarization as a function of phase angle to distinguish rock from ice.**
  - **Mini-RF data from Cabeus are consistent with ice present on the floor of Cabeus.**



Patterson et al. (2016) Icarus

Existing Data: PHYSICAL FORM

- LCROSS Visual Spectrometer
- Increasing Blue/Red interpreted as decreasing grain size from sublimating ice
- At least some ice is present in grains.



Heldmann et al., 2015

Volatiles: Current Status

Basic Questions	Answer	Data Needed
▪ What is the composition?	▪ Water ice confirmed via LCROSS & LADEE ▪ Hydrogen concentrations exist ▪ Hydrogen bearing material may or may not be water ice ▪ Other constituents include Hg, CO, H_2S, NH_3, and potentially some hydrocarbons	▪ *More complete identification of molecular and isotopic constituents and variations with position and time* ▪ *In situ sampling, sample return, isotopic analysis, active spectroscopy*

Volatiles: Current Status

Basic Questions

- What is the present-day distribution?

Answer

- Heterogeneities exist on many scales
  - Latitudinal
  - Orientation of slope
  - From one PSR to another
  - Within a PSR
  - On lateral scales of < 1 km
  - As a function of depth

Data Needed

- ***Higher spatial resolution data on volatiles on the surface and with depth in lunar polar regions***
- ***In situ sampling with subsurface access, radar, higher spatial resolution mapping***

Volatiles: Current Status

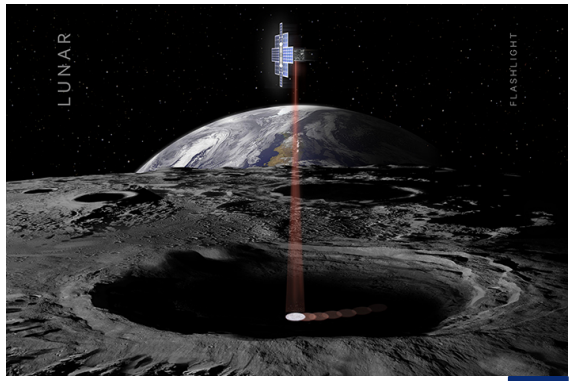
Basic Questions	Answer	Data Needed
▪ What is present-day abundance?	▪ Poleward of 80°, ~10^{11} kg of water ▪ Within PSRs, 1-2% by weight if H is in form of water ▪ Surface measurements consistent with < 2% frost	▪ *Understanding of the chemical form of H and the overall distribution* ▪ *In situ sampling, radar, remote sensing*

Volatiles: Current Status

Basic Questions	Answer	Data Needed
▪ What is the physical form?	▪ Pervasive, coherent ice sheets have been ruled out ▪ Some smaller ice grains have been detected ▪ Small amounts of surface frost are possible ▪ Pore-filling ice and hydrated minerals are also possible	▪ *Ground truth; Laboratory analysis of analogs* ▪ *In situ sampling, sample return, active spectroscopy*

Volatiles: Future Prospects

- **Resource Prospector to provide in situ "ground truth" on composition, distribution, abundance, physical form**
  - **Much anticipated!**
  - **Although sampling in permanent shadow is a goal, it will not do much exploration of them, or even sample the coldest regions**
- **Cubesats**
  - **Providing more information of surface veneer, surface frost, and hydrogen**
  - **Will improve understanding of distribution and composition**



Volatiles: Future Prospects

- **Additional, dedicated lunar volatiles missions are needed**
  - **Orbital**
  - **Landed**
  - **With exploration and science objectives**
- **Leveraging multiple techniques is key**
  - **Want information on surface content and volume content**
  - **Spectral data and in situ identification are complementary**
- **Understanding the system and processes is important**
  - **Follow up on new information on sources**
  - **Observe the redistribution process**
  - **Loss processes are linked to present distribution**

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